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13. ABSTRACT *(Maximum 200 words)*

In this program, we have studied, experimentally and theoretically, the fundamental properties of photorefractive spatial solitons and the features of the interactions between and among them. We brought the topic of photorefractive solitons to the very front of soliton science and of nonlinear optics. In our work, we have put much emphasis on studying properties and features that are universal to all solitons in nature, even to those in fields that are very remote from optics. We have discovered a family of entirely new solitons: Incoherent Solitons, which can exist in any non-instantaneous nonlinear media in nature. We have shown that solitons interacting in full 3D media manifest particle properties (such as conservation of angular momentum) which a decade ago were thought to be absurd with respect to solitons. Finally, we have demonstrated the feasibility of a list of applications that are unique to photorefractive solitons, the most important ones being (1) nonlinear frequency conversion in soliton-induced waveguides, and (2) fixing 2D solitons into the crystalline lattice of the nonlinear medium: Integrated Optics in 3D. At the beginning of this program, there were not more than 3-4 additional groups in the US studying optical spatial solitons, and not more than 10 world wide. Today, much of it following our work, optical spatial solitons have become a platform for studies of all soliton phenomena, and have attracted more than 50 groups world wide. The best evidence for that in the number of participants in the last Conference on Nonlinear Guided Waves and Their Applications, which was doubled between from the 1996 and 1998 conferences to the 1999 conference.

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Photorefractive Spatial Solitons: Fundamentals and Applications

Abstract

In this program, we have studied, experimentally and theoretically, the fundamental properties of photorefractive spatial solitons and the features of the interactions between and among them. We brought the topic of photorefractive solitons to the very front of soliton science and of nonlinear optics. In our work, we have put much emphasis on studying properties and features that are universal to all solitons in nature, even to those in fields that are very remote from optics. We have discovered a family of entirely new solitons: Incoherent Solitons, which can exist in any non-instantaneous nonlinear media in nature. We have shown that solitons interacting in full 3D media manifest particle properties (such as conservation of angular momentum) which a decade ago were thought to be absurd with respect to solitons. Finally, we have demonstrated the feasibility of a list of applications that are unique to photorefractive solitons, the most important ones being (1) nonlinear frequency conversion in soliton-induced waveguides, and (2) fixing 2D solitons into the crystalline lattice of the nonlinear medium: Integrated Optics in 3D. At the beginning of this program, there were not more than 3-4 additional groups in the US studying optical spatial solitons, and not more than 10 world wide. Today, much of it following our work, optical spatial solitons have become a platform for studies of all soliton phenomena, and have attracted more than 50 groups world wide. The best evidence for that in the number of participants in the last Conference on Nonlinear Guided Waves and Their Applications, which was doubled between from the 1996 and 1998 conferences to the 1999 conference.

Photorefractive Spatial Solitons: Fundamentals and Applications

Summary

Throughout this program, we have studied, experimentally and theoretically, the fundamental properties of photorefractive spatial solitons and the features of the interactions between and among them. We first summarize the highlight achievements of our research program and list the main achievements. Then, we provide a list of published papers classified, item by item, according to the various tasks we have proposed in our original Work Plan, 4 years ago.

Research Highlights

1. Incoherent solitons: Self-trapping of incoherent "white" light beams

Prior to our research, all soliton experiments and theories in nature (including all types of nonlinearities such as in fluids, plasma, and electromagnetic radiation) employed a coherent "pulse" (either a temporal pulse or a narrow beam in space). In other words, given the phase at a given location on the pulse (space or time) one can predict the phase anywhere on that self-trapped pulse. During the past year, we were able to **self-trap a fully incoherent light beam that originates from an incandescent light bulb**. In other words, we have taken a **beam (a "pulse" in space) upon which the phase varies randomly in time/space, yet it is still self-trapped**. This discovery became new milestone in Nonlinear Science: self-trapping of an incoherent wave-packet (pulse, in either space or time or both). It has opened the door for many new concepts, such as Coherence Control, "Cooling and Condensates" of optical fields, inducing single-mode waveguides using light from incoherent sources, etc.

For applications, this work brings about the possibility of using self-trapped beams from incoherent sources (such as Light Emitting Diodes: LEDs) for reconfigurable optical interconnect, beam steering, etc.

2. Three Dimensional Interactions between Spatial Solitons

Over the last 30 years much has been said about the similarity between solitons and particles. It is now well accepted that interacting solitons conserve energy and linear momentum. However, particles interacting in 3D can possess also angular momentum. Until 1992, all solitons demonstrated (either in time or in space, in ANY nonlinear media in which solitons can form, including fluids, plasma, etc.) have been one-dimensional. This is because all known solitons at that time were Kerr-like solitons, which fundamentally cannot support 2D self-

trapping (they become unstable). Since we have demonstrated (1993) that 2D optical beams can self-trap and form solitons in photorefractive media, we have had a unique opportunity to study full 3D interactions between solitons. In a series of experiments, we have shown that interacting 2D photorefractive solitons conserve energy, linear momentum and **angular momentum**. We have shown that when two such solitons collide (intersect) with initial trajectories that do not lie in the same plane, they attract and "bend" towards each other. The attraction between the solitons is simply due to the increased optical intensity in the region between the solitons, where their wave functions overlap, which increases (via the optical nonlinearity) the refractive index in that region. More light is then attracted (guided) in that region and the solitons attract each other. The solitons "capture" each other into orbit and spiral about each other when the attraction force between them exactly balances the "centrifugal" force. In other words, **we have demonstrated that two 2D spatial solitons interacting in a 3D system behave as a two-body system, very similar to celestial objects or to moving charged particles. At the time (1997), this was the first demonstration of this principle in any system that supports solitons.** Since then numerous groups have followed our footsteps and 3D soliton interactions now became a "hot topic".

3. Tunable nonlinear frequency conversion in soliton-induced waveguides

Several years ago we have proposed a fundamentally new application that is unique to photorefractive solitons: tunable nonlinear frequency conversion in soliton-induced waveguides. In general, waveguides induced by photorefractive solitons offer a large degree of tuning of all the waveguide parameters, so one can have high efficiency frequency conversion (due to a waveguide configuration) along with tunability. One method of tuning is mechanical: launching the solitons in different directions induces waveguides in different crystalline orientations and varies the phase matching condition. Therefore, one can simply rotate the crystal and tune the wavelength, just as if the nonlinear interaction is taking place in a bulk medium. Because the waveguide is not a fabricated waveguide, but rather is induced by the soliton, one simply rotates the waveguide as it is conventionally done with a bulk crystal. A more sophisticated method involves no mechanical movements: the propagation constants of the guided modes in waveguides induced by photorefractive solitons are tunable by varying the intensity ratio. Thus, one can hold the soliton beam at a fixed direction and position, and vary only its intensity while adjusting the applied voltage, so that one "walks" along the soliton existence curve, that is, the curve that describes all fundamental solitons in parameter space. This means that the phase matching condition, whether it is achieved by birefringence or by periodic poling, is tunable,

with a very large degree of accuracy. During 1998, we have preformed a series of preliminary experiments in our lab and were able to demonstrate a significant improvement in the conversion efficiency (in a short crystal) of second harmonic generation, over the same process with a diffracting beam, i.e., when the soliton induced waveguide is absent. The first paper on this project has appeared in 1999, and it presented an experimental demonstration of highly efficient SHG in soliton-induced waveguides. This seems to be the first real application of optical spatial solitons.

4. Photorefractive solitons at optical communication wavelengths (in InP)

Photorefractive semiconductors, such as InP and GaAs, offer fast nonlinear response, typically 100-1000 times faster than photorefractive oxides or silenites. Furthermore, some of them (InP) operate at optical communication wavelengths. However, their nonlinearity (electro-optic effect) is typically weak: their electro-optic coefficient is ~ 1.5 pm/v as compared to 1340 in SBN:75. In fact, until 1995 we believed that it was going to be very hard to generate solitons in photorefractive semiconductors. Despite the inherently small nonlinearity, during the past year we were able to demonstrate self-trapping of optical beams in photorefractive InP. What enables solitons in such materials is a fundamentally interesting intensity-resonance effect that give rise to a factor 10 (or larger) enhancement of the space charge field, over the externally-applied electric field (V/L). This intensity-resonance is driven by bipolar charge excitation, and it occurs when the density of photoexcited holes is roughly equal to the density of thermally-excited electrons. Using the intensity-resonance, we have demonstrated self-trapping of 1D and of 2D optical beams in Fe doped InP, at optical communication wavelength (λ=1.3 μm) and microsecond response time (see seventh transparency). These preliminary experiments pave the way to 2D reconfigurable optical interconnects using solitons. We have also investigate collisions of self-trapped beams in InP and found the necessary conditions for two such beams going through each other without exchanging energy (as we did for SBN), a task that is a pre-requisite for soliton interconnects.

5. Permanent "fixing" of photorefractive solitons

Recently, we have demonstrated a method of transforming the electronic space charge field is transformed into a crystalline lattice deformation, which results in permanent 2D waveguides impressed in the volume of a bulk nonlinear crystal. We have followed up on that by demonstrating permanently-fixed Y-junctions (beam splitter waveguides). This method, along with

other methods we are currently investigating, relies on reversing the crystalline polarity in selected regions. This technique enables one to design intricate 3D optical "circuitry" in the volume of a nonlinear crystal. One can envision numerous applications and devices for such 3D integrated optics: 3D interferometers, phase shifters, 2D Photonic Band-Gap structures, 2D waveguide arrays for Gap Solitons and many other exciting new ideas.

6. Photorefractive solitons with nanosecond formation time

Since the photorefractive response time for solitons scales with the dielectric relaxation, it is inversely proportional to the optical intensity. It is therefore logical that a large increase in the optical intensity and pulsed operation will shorten the response time considerably. However, high intensity short pulses can deplete the photorefractive dopant levels and forbid the existence of solitons in a high intensity regime. In 1996 we have shown theoretically that photorefractive solitons should exist also in the high intensity regime and should be observed on nanosecond time scales for oxides or silenites, and on sub-nanosecond scales for photorefractive semiconductors (InP and GaAs). During 1998, we have demonstrated short pulse (in the nanosecond range) operation of photorefractive solitons in SBN. We now plan to perform similar experiments with InP, in which the mobility is ~1000 times higher and thus the response time is ~1000 shorter, and attempt to observe sub-nanosecond photorefractive solitons.

A list of published papers classified according to the tasks in our original Work Plan

1.Experimental demonstration of bright 1-D low-intensity screening solitons

1.K. Kos, H. Meng, G. Salamo, M. Shih, M. Segev and G. C. Valley, *One-dimensional steady-state photorefractive screening solitons*, Rapid Communications, Physical Review E 53 , R4330 (1996).

2.Experimental studies of bright 2-D low-intensity screening solitons

1.M. Shih, P. Leach, M. Segev, M. Garrett, G. Salamo and G. C. Valley, *Two-dimensional steady-state photorefractive screening solitons*, Optics Letters 21, 324 (1996).

3. Experimental demonstration of dark 1-D and 2-D (vortex) low-intensity screening solitons

- Z. Chen, M. Mitchell, M. Shih, M. Segev, M. Garrett and G. C. Valley *Steady-state dark photorefractive screening solitons*, Optics Letters 21, 629 (1996).
- Z. Chen, M. Mitchell and M. Segev, *Steady-state photorefractive soliton-induced Y-junction waveguides and higher order dark spatial solitons*, Optics Letters 21, 716 (1996).
- Z. Chen, M. Segev, S. R. Singh, T. Coskun and D. N. Christodoulides, *Sequential formation of higher-order dark photorefractive spatial solitons: experiments and theory,* Journal of Optical Society of America B 14, 1407 (1997).
- Z. Chen, M. Shih, M. Segev, D. W. Wilson, R. E. Muller and P. D. Maker *Steady-state vortex screening solitons formed in biased photorefractive media,* Optics Letters 22, 1751, (1997)

4. Photorefractive vector solitons

1.D. N. Christodoulides, S. R. Singh, M. I. Carvalho and M. Segev, *Incoherently coupled soliton pairs in biased photorefractive crystals*, Applied Physics Letters 68, 1763 (1996).

2.Z. Chen, M. Segev, T. Coskun and D. N. Christodoulides, *Observation of incoherently coupled photorefractive spatial soliton pairs*, Optics Letters 21, 1436 (1996).

3.Z. Chen, M. Segev, T. Coskun, D. N. Christodoulides, Y. Kivshar and V. V. Afanasjev, *Observation of incoherently coupled dark-bright photorefractive spatial soliton pairs,* Optics Letters 21, 1821 (1996).

4.Z. Chen, M. Segev, T. Coskun, D. N. Christodoulides and Y. Kivshar, *Coupled photorefractive spatial soliton pairs,* Journal of Optical Society of America B 14, 3066 (1997).

5.M. Mitchell, M. Segev and D. N. Christodoulides, *Observation of multi-hump multi-mode solitons,* Physical Review Letters 80, 4657 (1998); See also commentary on this article in the *Random Samples* section of Science, vol. 280, 1697 (1998).

5. Theory of bright and dark screening solitons

2.M. Segev, M. Shih and G. C. Valley, *Photorefractive screening solitons of low and high intensity,* Journal of Optical Society of America B 13, 706 (1996).

3.B. Crosignani, P. DiPorto, A. Degasperis, M. Segev and S. Trillo, *Three dimensional optical beam propagation and solitons in photorefractive crystals,* Journal of Optical Society of America B 14, 3078 (1997).

6.Time-dependent theory of quasi-steady-state solitons

- B. Crosignani, P. DiPorto, M. Segev, G. Salamo and A. Yariv, *Nonlinear optical beam propagation and solitons in photorefractive media,* Nuovo Cimento, vol. 21(6), 1 (1998).

7. Experimental demonstration of high-intensity screening solitons

- K. Kos, G. Salamo and M. Segev, *High-intensity nanosecond photorefractive spatial solitons,* Optics Letters 23, 1001 (1998).

8. Collisions between screening solitons: theory and experiments

- M. Shih and M. Segev, *Incoherent collisions between two-dimensional bright steady-state photorefractive spatial screening solitons,* Optics Letters 21, 1538 (1996).
- M. Shih, Z. Chen, M. Segev, T. Coskun and D. N. Christodoulides, *Incoherent collisions between one-dimensional steady-state photorefractive screening solitons,* Applied Physics Letters 69, 4151 (1996).
- H. Meng, G. Salamo, M. Shih and M. Segev, *Coherent collisions of photorefractive solitons,* Optics Letters 22, 448 (1997).
- M. Shih, M. Segev and G. Salamo, *Three dimensional spiraling of interacting spatial solitons,* Physical Review Letters 78, 2551 (1997).
- M. Shih, M. Segev, G. Salamo and Y. Kivshar, *Do interacting spatial solitons conserve angular momentum?,* Optics and Photonics News, *Special Issue: Optics in 1997,* vol. 8(12), 43 (1997).
- H. Meng, G. Salamo and M. Segev, *Primarily isotropic nature of photorefractive screening solitons and the interactions between them,* Optics Letters 23, 897 (1998).
- A. Buryak, Y. S. Kivshar, M. Shih and M. Segev, *Induced coherence and stable soliton spiraling,* Physical Review Letters 82, 81 (1999).

- G. Stegeman and M. Segev, *Optical spatial solitons and their interactions: universality and diversity,* Invited Paper, Special Issue on Frontiers in Optics, Science 286, 1518 (1999).

9.Arrays of screening solitons: theory and experiments

- S. Lan, E. DelRe, Z. Chen, M. Shih and M. Segev, *Directional coupler using soliton-induced waveguides,* Optics Letters 24, 475 (1999).
- E. A. Ostrovskaya, Y. S. Kivshar, Z. Chen and M. Segev, *Interactions between vector solitons and solitonic gluons,* Optics Letters 24, 327 (1999).

10. Photorefractive soliton beam steering

- C. Anastassiou, M. Segev, K. Steiglitz, J. A. Giordmaine, M. Mitchell, M. Shih, S. Lan, and J. Martin, *Energy exchange interactions between colliding vector solitons,* Physical Review Letters 83, 2332 (1999).

11. Experiments and theory of photovoltaic solitons

- M. Taya, M. C. Bashaw, M. M. Fejer, M. Segev and G. C. Valley, *Y-junctions arising from dark-soliton propagation in photovoltaic media*, Optics Letters 21, 943 (1996).
- Segev, M. C. Bashaw, G. C. Valley, M. M. Fejer and M. Taya, *Photorefractive-photovoltaic spatial solitons*, Journal of Optical Society of America B 14, 1772 (1997).
- Z. Chen, M. Segev, D. W. Wilson, R. E. Muller and P. D. Maker *Self-trapping of an optical vortex by use of the bulk photovoltaic effect*, Physical Review Letters 78, 2948 (1997).
- C. Anastassiou, M. Shih, M. Mitchell, Z. Chen and M. Segev, *Optically-induced photovoltaic self-defocusing to self-focusing transition*, Optics Letters 23, 924 (1998).

12. Optical guidance using screening solitons

- M. Shih, M. Segev and G. Salamo, *Circular waveguides induced by two-dimensional bright steady-state photorefractive spatial screening solitons,* Optics Letters 21, 931 (1996).
- M. Shih, Z. Chen, M. Mitchell and M. Segev, *Waveguides induced by photorefractive screening solitons,* Journal of Optical Society of America B 14, 3091 (1997).
- M. Klotz, H. Meng, M. Segev, and S. R. Montgomery, *Fixing the photorefractive soliton,* Optics Letters 24, 77 (1999).
- Z. Chen, M. Segev, D. N. Christodoulides, and R. S. Feigelson, *Waveguides formed by incoherent dark solitons,* Optics Letters 24, 1160 (1999).

- E. DelRe, M. Tamburrini, M. Segev, A. Agranat and R. Della Pergola, *Spontaneous self-trapping of optical beams in metastable paraelectric crystals,* Physical Review Letters 83, 1954 (1999).

13. Frequency conversion in soliton-induced waveguides

- S. Lan, M. Shih and M. Segev, *Self-trapping of 1D and 2D Optical Beams and Induced Waveguides in Photorefractive $KNbO_3$,* Optics Letters 22, 1467 (1997).
- S. Lan, M. Shih, G. Mizell, J. A. Giordmaine, Z. Chen, C. Anastassiou, and M. Segev, *Second harmonic generation in waveguides induced by photorefractive spatial solitons,* Optics Letters 24, 1145 (1999).

<u>**New Spatial Solitons topics that were discovered during the course of the "old" ARO program**</u>

A. Spatial solitons at optical communications wavelength

- M. Chauvet, S. A. Hawkins, G. Salamo, M. Segev, D. F. Bliss and G. Bryant, *Self-trapping of planar optical beams using the photorefractive effect in InP:Fe*, Optics Letters 21, 1333 (1996).
- M. Chauvet, S. A. Hawkins, G. Salamo, M. Segev, D. F. Bliss and G. Bryant, *Self-trapping of two-dimensional optical beams and light-induced waveguiding in InP:Fe at telecommunication wavelengths,* Applied Physics Letters, 70, 2499 (1997).

B. Incoherent Solitons

- M. Mitchell, Z. Chen, M. Shih and M. Segev, *Self-trapping of partially spatially-incoherent light*, Physical Review Letters 77, 490 (1996).
- M. Mitchell, Z. Chen, M. Shih and M. Segev, *Self-trapping of partially spatially-incoherent light beams*, Optics and Photonics News, *Special Issue: Optics in 1996*, vol. 7(12), p. 17, December 1996.
- D. N. Christodoulides, T. Coskun, M. Mitchell and M. Segev, *Theory of incoherent self-focusing in biased photorefractive media,* Physical Review Letters 78, 646 (1997).
- M. Mitchell and M. Segev, *Self-trapping of incoherent white light,* Nature, vol. 387, 880 (1997). See also commentary on this article in the *News and Views* section of the same issue: Nature, vol. 387, 854 (1997).
- M. Mitchell, M. Segev, T. Coskun and D. N. Christodoulides, *Theory of self-trapped spatially-incoherent light beams,* Physical Review Letters 79, 4990 (1997).
- D. N. Christodoulides, T. Coskun, M. Mitchell and M. Segev, *Multimode incoherent spatial solitons in logarithmically saturable nonlinear media,* Physical Review Letters 80, 2310 (1998).

- T. Coskun, D. N. Christodoulides, M. Mitchell, Z. Chen and M. Segev, *Dynamics of incoherent bright and dark self-trapped beams and their coherence properties in photorefractive crystals,* Optics Letters 23, 418 (1998).
- Z. Chen, M. Mitchell, M. Segev, T. Coskun and D. N. Christodoulides, *Self-trapping of dark incoherent light beams*, Science 280, 889 (1998).
- D. N. Christodoulides, T. Coskun, M. Mitchell, Z. Chen and M. Segev, *Theory of dark incoherent solitons,* Physical Review Letters 80, 5113 (1998).
- M. I. Carvalho, T. Coskun, D. N. Christodoulides, M. Mitchell and M. Segev, *Coherence properties of multi-mode incoherent spatial solitons in non-instantaneous Kerr media,* Physical Review E 59, 1193 (1999).
- Z. Chen, M. Mitchell, M. Segev, T. Coskun and D. N. Christodoulides, *Dark incoherent solitons,* Optics and Photonics News, *Special Issue: Optics in 1998*, vol. 9(12), 48 (1998).
- T. Coskun, D. N. Christodoulides, Z. Chen and M. Segev, *Dark incoherent soliton splitting and "phase-memory" effects: theory and experiments,* Rapid Communications, Physical Review E 59, R4777 (1999).

C. Solitons in Photorefractive Centrosymmetric Media

- M. Segev and A. Agranat, *Spatial solitons in centrosymmetric photorefractive media*, Optics Letters 22, 1299 (1997).
- E. DelRe, B. Crosignani, M. Tamburrini, M. Segev, M. Mitchell, E. Refaeli and A. J. Agranat, *One-dimensional steady-state photorefractive spatial solitons in centrosymmetric paraelectric KLTN,* Optics Letters 23, 421 (1998).
- E. DelRe, M. Tamburrini, M. Segev, and A. J. Agranat, *2D photorefractive spatial solitons in centrosymmetric paraelectric KLTN,* Applied Physics Letters 73, 16 (1998).

Altogether, we have published more than 50 papers on work supported by this program, including papers in Nature, Science, Physics Today and Physical Review Letters.

Personnel showing advanced degrees.

Dr. Matthew Mitchell, Graduated his Ph.D. in July 1998 (at Princeton University)

Dr. Ming-feng Shih, Graduated his Ph.D. in July 1998 (at Princeton University)

Mr. Marin Soljacic, Graduated his M.A. in May 1997 (at Princeton University)
(will be graduating his Ph.D. in 2000)

Mr. Charalambos Anastassiou, Graduated his M.A. in May 1998 (at Princeton University)
(will be graduating his Ph.D. in 2001)

Mr. Song Lan, Graduated his M.A. in May 1998 (at Princeton University)
(will be graduating his Ph.D. in 2001)

Dr. Matthew Klotz, Graduated his Ph.D. in 1998 (at the University of Arkansas)

Mr. Konstantin Kos. Graduated his M.A. in 1998 (at the University of Arkansas)